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AND BEYOND

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Acceleration of Particles in the Earth's Shock Transition Region and Beyond

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Abstract: Pulses of high energy electrons were observed in the vicinity of the bow shock of the terrestrial magnetosphere with both the Au-Si surface barrier solid state detector (the front detector of the cosmic-ray telescope of the University of Chicago) and the GM counter (University of California) on board the IMP-I satellite. These particle pulses were also detected inside the shock transition region with GM counters in earlier satellites. There is experimental evidence that these electrons are accelerated in the shock transition region. By comparing the counting rates of the solid state detector and that of the GM counter on board IMP-I, the energy spectrum of the electrons may be estimated. If the integral spectrum is expressed as $F = F_0 E^{-\gamma}$, the value of γ varies from + 2.5 to + 4.5.

Beyond the shock transition region up to the apogee of the IMP-I satellite (200,000 km), pulses of high energy particles were also observed with the Au-Si solid state detector prior to the arrival of the 27-day recurrent solar plasma of enhanced velocity. It is suggested that these are particles accelerated in space by multiple shock waves associated with the co-rotating shock front.

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The mechanism of acceleration of high energy particles in nature is of importance for understanding the origin of cosmic radiation. The purpose of this paper is to report the observation of pulses of electrons in the earth's shock transition region and beyond with the IMP-I satellite, and to present experimental evidence showing that they are accelerated in these regions. The acceleration by the Fermi mechanism is discussed.

IMP-I (Explorer 18) was launched on November 27, 1963. Its initial apogee was on the sunlit side of the earth at an angle to the sun of 32.7° and at a geocentric distance of 31.9 earth radii. On board the satellite there were two detector systems which have energy thresholds low enough for detecting low energy electrons. They are the Geiger-Muller counter of the University of California and the gold-silicon surface barrier detector, the front detector D_1 , of the cosmic ray telescope of the University of Chicago. Their energy thresholds for the detection of electrons are 40 kev and 30 kev respectively.

Figures 1A-C show the counting rates of D_1 , averaged over four telemetry sequences (~ 328 sec), plotted as a function of the geocentric range of the satellite for the first inbound, second outbound and inbound passes. For convenience of discussion, the time scale in UT (days are numbered from Jan. 1, 1963) is also included along with the geocentric range. The arrow with a letter M indicates the position of the boundary of the magnetosphere and the arrow with a letter S indicates the position of the bow shock as determined by Ness et al. (1964) with a magnetometer on board the same satellite.

From Fig. 1A, it is seen that the space may be divided into three

regions according to the D_1 counting rates: 1) the magnetosphere (Region I) where the counting rates go off scale, reaching thousands per second; 2) the interplanetary space (Region III) where the counting rates are low and only slowly varying; and 3) the region of interaction between the solar wind and the terrestrial magnetic fields (Region II) where the counting rates abruptly increase for short intervals of time above the interplanetary value. These counting rate spikes are identified as electron pulses in the region of interaction between the solar wind and the terrestrial magnetic field. We shall present evidence that these electrons are locally accelerated in this region.

The number and spatial distribution of counting rate spikes depend strongly upon interplanetary conditions, such as the solar wind velocity. For example, during the first inbound pass, the counting rates in Region III, about 3 counts/sec, were due to cosmic ray particles. These observations represent a normal, quiescent state in space with a solar wind at average velocity. However, during the second outbound and inbound pass (Fig. 1B and 1C) when the solar plasma of enhanced velocity from an active region at the sun swept over the earth and the satellite, the electron spikes beyond the magnetosphere greatly increased in number and intensity, and the distribution of the spikes extended far out to distances greater than 200,000 km. The arrival of the high velocity plasma was detected by plasma probes on board IMP-I at 2111 Dec. 2, 1963 UT (Bridge, et al. 1964; Wolfe, et al. 1965). It is interesting to note that many of the spikes at large distances appeared many hours prior to that time. We suggest that these spikes are

particles accelerated in the interplanetary space by multiple shock waves. Details will be discussed later in this paper.

In Figure 1C the background counting rate gradually rose from its normal value to approximately 30 counts per second. This background is due to the arrival of a 27-day recurring stream of protons with energies below 30 Mev. The results are discussed in another paper presented in this conference (Fan, Gloeckler and Simpson).

The mica window GM counter of the University of California was designed for the detection of electrons only (Anderson, et al. 1965). The comparison of the electron spikes observed by the GM electron detector and that by the D_1 solid state detector in Region II for the second inbound pass is shown in Fig. 2. The one to one correspondence is apparent.

The important difference between the GM counter and the solid state detector in counting electrons is that the response of the former is a linear function of the flux whereas the response of the latter is a non-linear function, since the solid state detector counts electrons individually at high energies and by pile-up effect at low energies. Consequently, it becomes possible to estimate the spectrum by comparing the counting rates of the two detectors. A detailed analysis will be published elsewhere (Fan, Gloeckler and Simpson, 1965).

Fig. 3 shows the correlation between the peak counting rates of the electron spikes as observed with the GM counter and with the D_1 solid state detector. If we assume that the electrons in the spikes observed in the shock transition region and beyond have an inverse power integral spectrum:

$$F(E) = F_0 E^{-\gamma} \quad \text{electrons/cm}^2 \text{ sec. ster}$$

where F_0 and γ are two positive constants and E is in kev, by knowing the characteristics of the detector systems, the correlation function between the D_1 counting rate C and the GM counter counting rate R can be readily calculated. This function for $\gamma = 2.5, 3, 3.5, \text{ and } 4.5$ is dotted in Fig. 3. The observed γ varied from 2.5 to 4.5. Montgomery et al. (1965) obtained values of 3.2, 3.4 and 4.2 for the electron pulses at large sun-earth-probe angles mostly inside the shock transition region. The present values are in remarkable agreement with their results although they were measured at different times and locations.

In an earlier publication (Fan, et al. 1964) it was pointed out that the electrons observed as spikes in the shock transition region are most likely locally accelerated near the bow shock. On the other hand, Anderson, et al. (1965) suggested that these electrons are of magnetospheric origin. A strong argument favoring local acceleration comes from the examination of the variation of the energy spectra of the electrons in the spikes shown in Figure 3 and the positions of the spikes shown in Fig. 2. The exponent for the spectrum is remarkably narrow in range of values with a tendency of hardening with the distance of the spike from the magnetosphere. If these were the electrons escaping from the magnetosphere, the more distant electron spikes would have softer energy spectra than the spikes near the magnetosphere. Since this is not the case, we believe this is evidence against electrons escaping from the magnetosphere. Independent evidence for acceleration of particles in this region is given by the dawn-evening asymmetry

of the electron spike distributions observed by Montgomery et al. (1965).

Arguments in favor of various mechanisms of acceleration of the electrons which appear in the counting rate spikes depend upon the position of the spikes relative to the magnetosphere and the earth bow shock. From Fig. 1A-C, it is seen that the electron spikes are found in four regions: in the transition region, at the shock front, within a few earth radii beyond the bow shock, and at geocentric range approximately 20 earth radii and beyond. Those spikes which coincide with the shock front could well represent a quasi-stationary spatial structure. On the other hand, it was pointed out by Jokipii and Davis (1964) that the electron spikes a few earth radii outside the shock front cannot be a spatial structure since in this region the magnetic lines of force are flowing with the solar wind and thus the electrons would be immediately swept away with the magnetic field. Consequently they suggested that the electrons are accelerated by the Fermi mechanism (Fermi, 1954) between the bow shock and the approaching irregularities carried by the solar wind. As soon as the "jaws" close the electrons are swept into the transition region, especially at large sun-earth-probe angles.

The counting rate spikes at great distances which were observed during the second outbound and inbound pass (Fig. 1B and 1C) were again observed approximately 27 days later and in the following solar rotation when high velocity solar wind from the same active region of the sun swept over the satellite and the earth. The evidence for later sequences is unclear because the satellite gradually entered into the tail region of the magnetosphere. A detailed study revealed that they appeared prior to the gradual increase in the general background which leads

into the onset of the recurring solar proton stream. This time sequence is illustrated in Fig. 4 where the D_1 counting rates and interplanetary magnetic field strength F , field vector angles θ and ϕ , the variances of the three components of the field, X_{se} , Y_{se} , Z_{se} , as measured with the onboard magnetometer of Ness et al. (1964) are plotted as a function of time (UT). About four hours after several electron spikes had been detected (beyond the range of 20 earth radii), the D_1 counting rate increased gradually from its normal value of below 3 counts/sec to above 3 counts/sec. The increase seems to coincide with an abrupt increase in the field strength F and a rapid change in the vector angles θ and ϕ as indicated by an arrow in Fig. 4. The fluctuations in the counting rates prior to the sudden commencement seem to correlate to that of the magnetic field. Although the physical implications of these correlations is not clear at the present moment, we would like to take these as evidence of shock waves produced by the recurrent solar streams and the electron spikes (maybe even some of the background) as particles accelerated by the co-rotating shock front.

We wish to emphasize that if the acceleration of the electron spikes observed at geocentric distances to 200,000 km, at the bow shock, and inside the transition region are to be explained by a single process, then the Fermi mechanism is likely to be the type. The assumption that the electrons are accelerated at the shock and beyond and then carried into the shock transition region and the magnetospheric tail by convection appears to be the most persuasive.

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Captions

- Fig. 1A-C The counting rate of D_1 vs. the geocentric distances in 10^3 km of the satellite IMP-I. Solar plasma of enhanced velocity was detected by an onboard plasma probe at 336-2117 UT. The arrow with a letter M indicates the position of the boundary of the magnetosphere and the arrow with a letter S indicates the position of the bow shock as determined by Ness et al. (1964).
- Fig. 2. The comparison of the counting rates of the GM counter (University of California) and that of the Au-Si solid state detector (University of Chicago).
- Fig. 3. The correlation of the counting rates of the electron pulses in the shock transition region and beyond, measured with the Au-Si detector with that measured with the GM counter.
- Fig. 4. The correlation of the electron spikes and gradual increase in the D_1 counting rates in interplanetary space with the variances of the magnetic field. F is the field strength, θ and ϕ are two polar vector angles, and X_{se} , Y_{se} , Z_{se} are variances of the three components of the magnetic field.

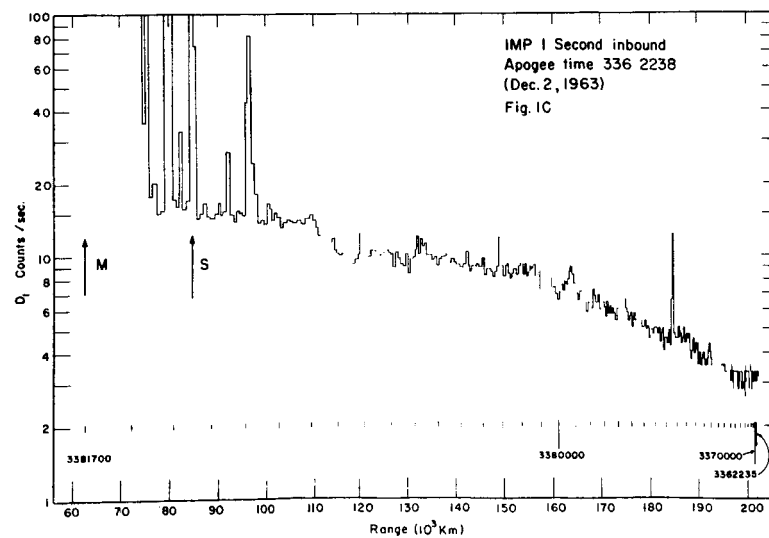
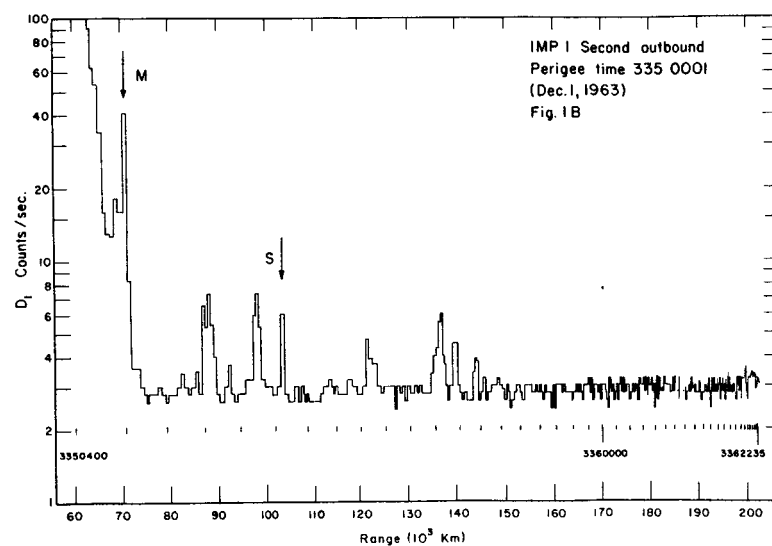
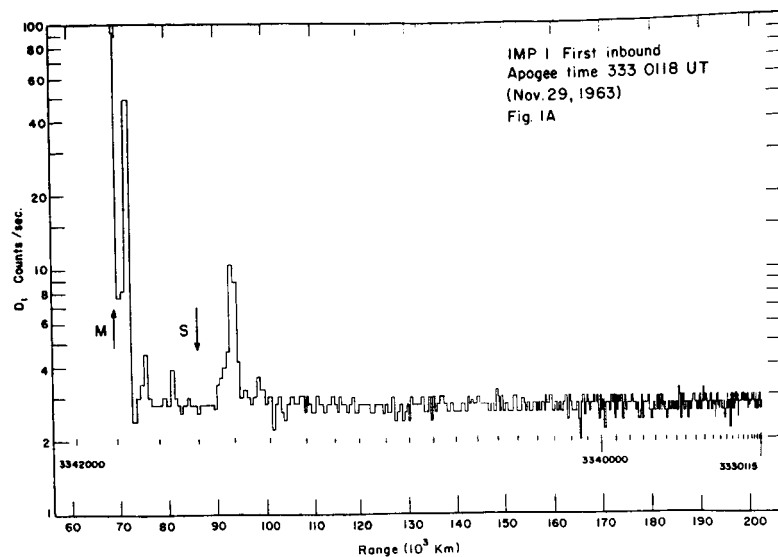


Fig. I

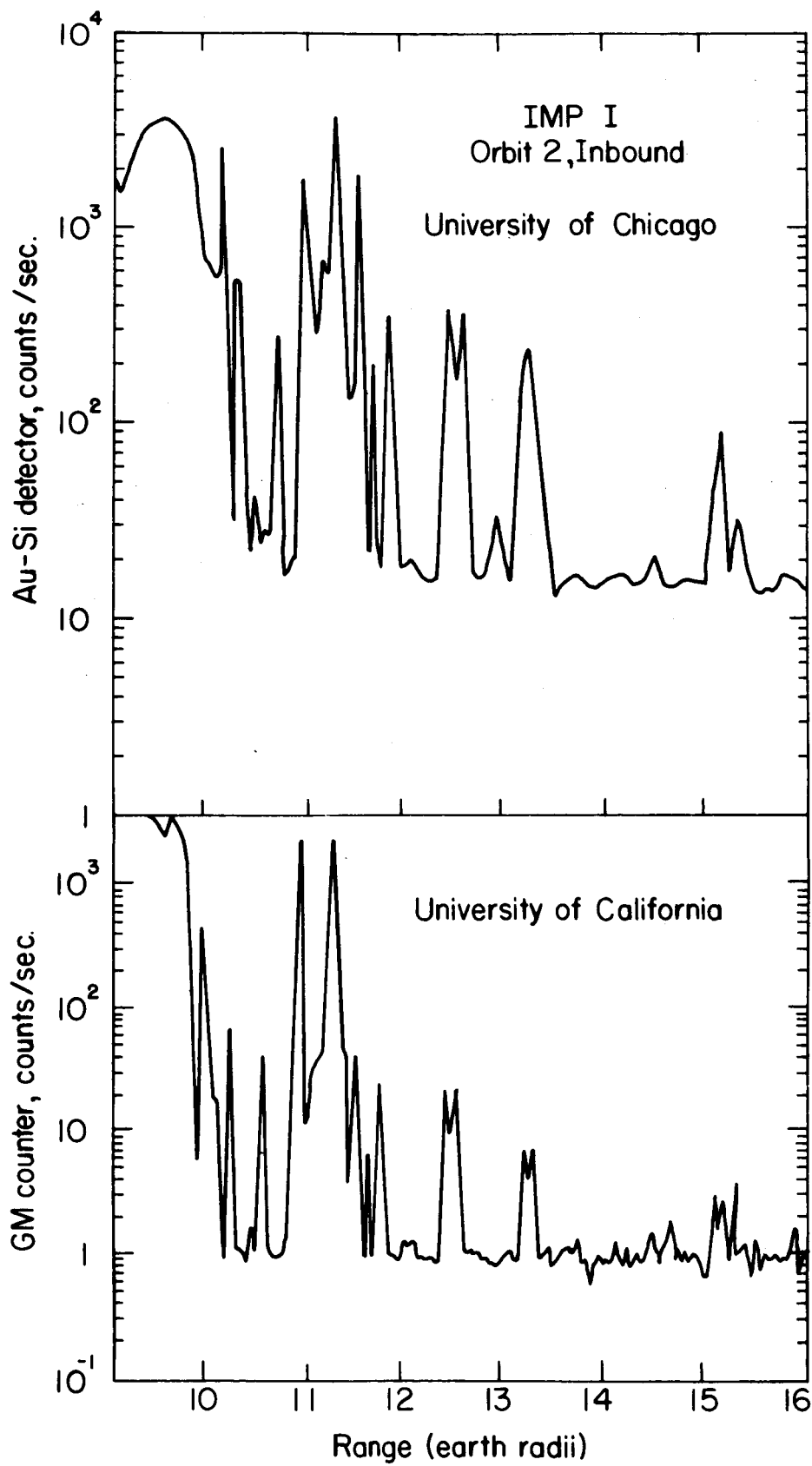


Fig. 2

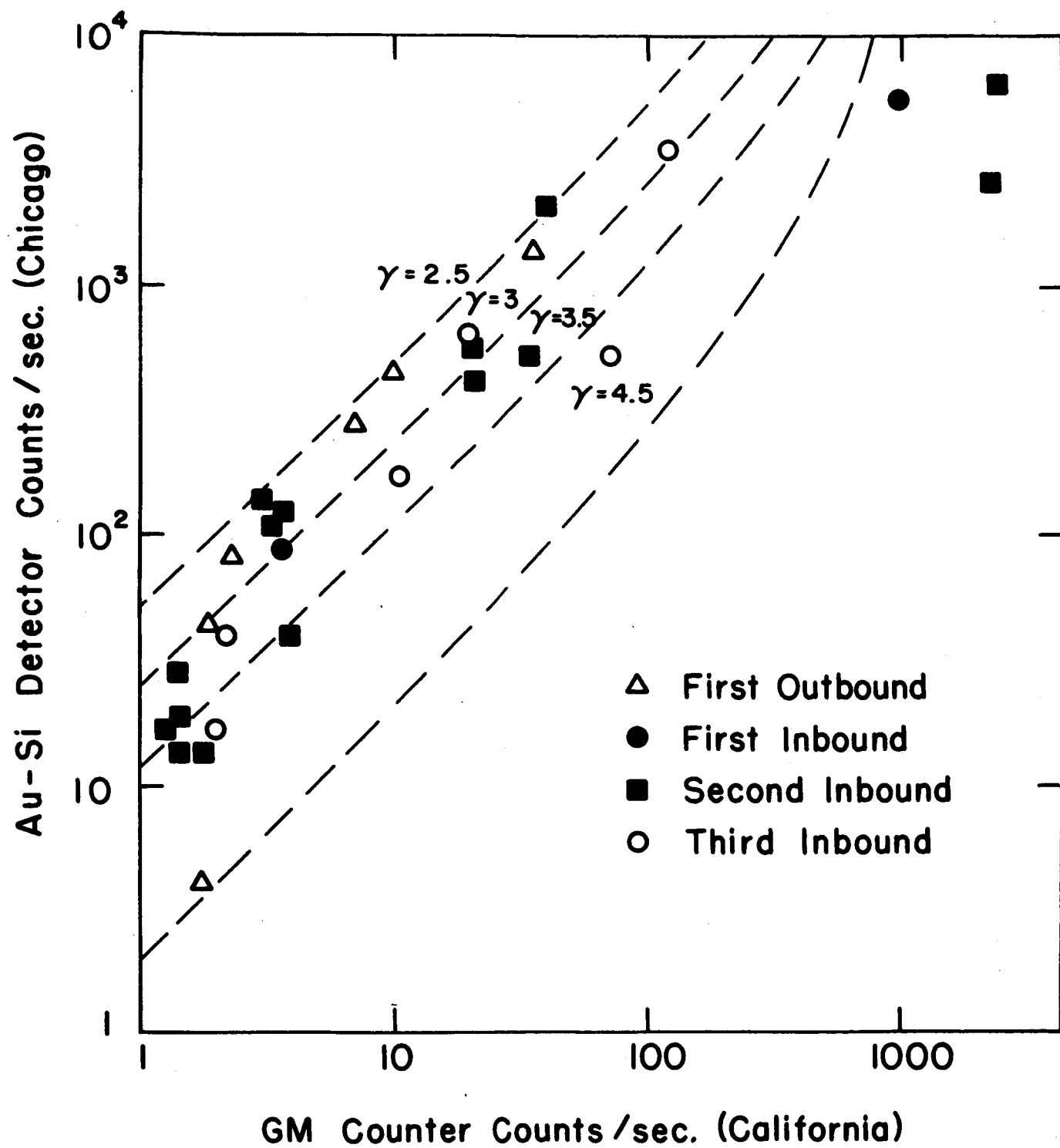


Fig. 3

